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Abstract

: This paper establishes a methodology to quantify pile setup by using recent field test data that was presented in a companion paper for steel H-piles driven in cohesive soils. Existing methods found in literature for the same purpose either require restrikes of piles onsite or are developed for a specific soil type and seldom use easily quantifiable soil properties, despite their significant influence on pile setup. Following a critical evaluation of the existing methods, a new approach for estimating pile setup was developed using dynamic measurements and analyses in combination with measured soil properties, such as the horizontal coefficient of consolidation, undrained shear strength, and the standard penetration test N value. Using pile setup information available in the literature, the proposed approach has shown that it provides good estimates for the setup of steel H-piles, as well as for other types and sizes of driven piles.

Keywords

Pile setup, Undrained shear strength, SPT, Coefficient of consolidation, Restrikes, Static load test

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Comments

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**PILE SETUP IN COHESIVE SOIL: Analytical Quantifications and Design
Recommendations**

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PILE SETUP IN COHESIVE SOIL: Analytical Quantifications and Design Recommendations

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ABSTRACT: This paper establishes a methodology to quantify pile setup by using recent field test data that was presented in a companion paper for steel H-piles driven in cohesive soils. Existing methods found in literature for the same purpose either require restrikes of piles onsite, or are developed for a specific soil type and seldom use easily quantifiable soil properties despite their significant influence on pile setup. Following a critical evaluation of the existing methods, a new approach for estimating pile setup was developed using dynamic measurements and analyses in combination with measured soil properties, such as the horizontal coefficient of consolidation, undrained shear strength and/or Standard Penetration Test *N*-value. Using pile setup information available in literature, the proposed approach has shown that it provides good estimates for the setup of steel H-piles, as well as for other types and sizes of driven piles.

CE Database Keywords: Pile Setup; Undrained Shear Strength; SPT; Coefficient of Consolidation; Restrikes; Static Load Test.

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INTRODUCTION

The existing pile setup estimation methods available in literature require restrikes and/or load testing and although an accurate integration of pile setup will lead to cost-effective foundation designs, these methods have not been incorporated into the AASHTO (2010) Specifications. Static load or dynamic restrike tests performed over an adequate period of time are currently recommended in AASHTO (2010) to quantify pile setup. Alternatively, a methodology to estimate pile setup based on soil properties would be easier to implement, as well as cost effective. Using dynamic and static investigations on steel H-piles, it is shown in a companion paper (Ng et al. 2011) that pile setup in cohesive soils is heavily dependent on the horizontal coefficient of consolidation, undrained shear strength and/or SPT N -value. Recognizing that a reliable method to estimate pile setup based on soil properties does not exist, a new methodology is proposed herein based on recent field test data. The accuracy of the proposed method was verified using both local and external case studies.

EXISTING PILE SETUP ESTIMATION METHODS

Five pile setup estimation methods available in literature are chronologically summarized in Table 1. Pei and Wang (1986) proposed an empirical setup equation specifically for Shanghai's soils and reinforced concrete piles. Huang (1988) concluded that this method provided comparable pile setup estimation for steel H-piles (HP 360×174) installed in similar Shanghai soils. However, this method does not incorporate any soil properties and requires the determination of a maximum pile resistance (R_{max}) defined at 100% consolidation of the surrounding soil, which is usually difficult to estimate in practice.

Zhu (1988) suggested the use of an equation based on cohesive soil sensitivity (S_t) to estimate pile resistance at the 14th day (R_{14}) after the end of driving (EOD). In the case study of a 34-m long, 600-mm square pre-stressed concrete pile, driven in a coastal area of East China with a soil profile of mostly clay and silt, Zhu (1988) predicted that pile resistance at day 14 was between 4600 and 4900 kN, which reasonably matched the load test measured resistance of 4800 kN. The practicality of this method is limited because it is unclear how pile resistance, including pile setup, should be estimated at any time other than the 14th day.

Skov and Denver (1988) proposed a setup equation that required a restrike to be performed at 1 day from EOD (t_o) to estimate a reference pile resistance (R_o). They recommended the setup factor (A), which describes the rate of increase in pile resistance over time, of 0.6 based on 250-mm square concrete piles driven into Yoldia clay. However, it has been shown that the variation of soil and pile types would vary the value of A between 0.1 and 1.0 (Bullock et al., 2005; and Yang and Liang 2006), creating uncertainties in the estimation of pile setup. Using recent restrikes and static load tests (SLT) of five piles summarized in the companion paper (Ng 2011), this issue is investigated in Figure 1. This figure confirms that the Skov and Denver (1988) method, with the recommended A value of 0.60, does not match the field test results. However, an agreement can be achieved if the A value is reduced to 0.074, which is even smaller than the range reported by Bullock et al. (2005) and Yang and Liang (2006). The possibility of estimating the value of A based on soil properties has not been published in literature, which limits the use of this approach in design practice.

To improve Skov and Denver's (1988) method, Svinkin and Skov (2000) took into account the actual time after EOD by allowing reference pile resistance to be estimated at the EOD condition, providing the pile setup estimation independent of the time of first restrike at t_o . In the formulation process, Skov and Denver's A value was replaced with an alternative factor (B). The authors suggested that the time for EOD (t_{EOD}) was to be 0.1 day, which has negligible effects on pile setup estimation while allowing the use of the logarithmic time scale. Compared to Skov and Denver's (1988) method, this method provides more economic means for pile setup assessment. However, estimation of the B value based on soil properties is not available since it is usually determined from restrikes.

Karlsrud et al. (2005) proposed an empirical pile setup method using the plasticity index (PI) and overconsolidation ratio (OCR) based on a database from the Norwegian Geotechnical Institute (NGI). This database consists of 36 well-documented static load tests on both open and closed-end steel pipe piles, with outer diameters greater than 200 mm and embedded pile lengths greater than 10 m. Karlsrud et al. (2005) suggested that the reference pile resistance (R_{100}) should be the resistance at 100 days after EOD, assuming that the excess pore water pressure induced by pile installation is fully dissipated. Fellenius (2008) concluded that complete pore water dissipation

during the first 100 days was not accurate after observing the dissipation of a single 300-mm diameter, hexagonal, precast concrete pile driven in soft Marine clay in Sweden occur after about six months. To examine the accuracy of this method for steel H-piles, Iowa State University (ISU) field test results were used to extrapolate the R_{100} for each test pile by best-fitting a logarithmic trend through the estimated pile resistances. The estimated resistances were determined using the CAsE Pile Wave Analysis Program (CAPWAP) from restrikes, the measured pile resistances were obtained from static load tests, and the R_{100} values were later read off from the trend at 100 days. The estimated pile resistances and the measured pile resistance for each test pile were normalized by the respective R_{100} to determine the pile resistance ratio (R_t/R_{100}), as plotted in Figure 2. Using the estimated R_{100} values as well as the average PI and OCR values of each site, the pile resistances (R_t) were estimated at different times within 100 days using the pile setup equation of Karlsrud et al. (2005), as plotted in Figure 2. The poor comparison between the ISU field test results and the Karlsrud et al. (2005) method suggests that this pile setup method cannot be applied to steel H-piles driven into glacial clays.

PILE SETUP

Observations

The field test results for five HP 250 × 62 steel piles embedded in cohesive soils show a linear relationship between normalized pile resistance (R_t/R_{EOD}) and logarithmic normalized time ($\text{Log}_{10}(t/t_{EOD})$), as plotted in Figure 3, where t refers to time after EOD condition. Among the eight hammer blows on average, delivered on each test pile during each restrrike test, the third blow was selected for CAPWAP analyses. The third blow did not necessarily have the highest PDA measured resistance, but did include the most representative PDA record. To compensate for pile resistance gain resulting from the additional pile penetration during restrikes, the normalized pile resistance was corrected by multiplying it by the normalized pile embedded length (L_{EOD}/L_t). This approach was satisfactory due to the minimal end bearing contribution to total pile resistance. In order to satisfy the logarithmic relationship and consider the immediate gain in pile resistance measured after EOD, the time at EOD (t_{EOD}) was assumed as 1 minute. While Figure 3 presents the CAPWAP setup results for the five test piles via linear best-fit lines, Figure 4 shows a similar evaluation for the Wave Equation Analysis Program (WEAP) with the SPT N -value based method (SA as referred by Pile Dynamics, Inc. 2005). Although the WEAP-

SA method was used herein, Ng et al. (2010) concluded that other WEAP based methods yielded comparable pile resistance estimations such as the Federal Highway Administration (FHWA) DRIVEN program, which uses undrained shear strength (S_u) to define cohesive soil strength. In both cases, each best-fit line was generated using a regression analysis based on the restrike results indicated by open markers. With the exception of the WEAP analysis results of ISU3, which had a relatively short time interval of about 6 minutes between restrikes, which lead to a rather similar blow count (16 blows per 300 mm) at BOR1, BOR2 and BOR3, all linear relationships shown in Figure 3 and Figure 4 fit the linear trend for the normalized pile resistance adequately. This was confirmed by the coefficients of determination (R^2), as shown in the figures, in the range of 0.87 to 0.98. For a comparative purpose, static load test results, which are indicated by solid markers, are also included. The slope (C) of the best-fit line describes the rate of pile resistance gain, i.e., a larger slope indicates a higher percentage of the pile setup, providing a larger normalized pile resistance (R_t/R_{EOD}) at a given time t . Since CAPWAP provides more accurate estimations than WEAP, as demonstrated by higher R^2 values, Figure 3 shows that ISU2 (short-dashed line) embedded in relatively soft cohesive soil (i.e., weighted average SPT N -value of 5) has the largest slope of 0.167 while ISU5 (long-dashed and dotted line) embedded in relatively stiff cohesive soil (i.e., weighted average SPT N -value of 12) has the smallest slope of 0.088.

Pile Setup Factor

Given that all tested steel H-piles were the same size, additional pile penetration was corrected using the normalized embedded pile length (L_{EOD}/L_t) and the pile setup factor (C) for a given site as a constant that does not vary with time (t) as shown in Figure 3 and Figure 4. It was concluded that the pile setup factor (C) depends on the surrounding soil properties. Adopting Skov and Denver's (1988) method (see Table 1) and substituting R_{EOD} for R_o , t_{EOD} for t_o and C for A value, the general form of the proposed pile setup equation that describes the best-fit lines shown in Figure 3 and Figure 4 can be written as

$$\frac{R_t}{R_{EOD}} = \left[C \times \log_{10} \left(\frac{t}{t_{EOD}} \right) + 1 \right] \left(\frac{L_t}{L_{EOD}} \right) \quad (1)$$

In order to characterize the pile setup factor (C) with soil properties, the normalized embedded pile length (L_t/L_{EOD}), which ranged between 1 and 1.06 based on all field tests, was assumed to be unity. Since the pile setup factor (C) was determined based on the normalized pile resistance

(R_t/R_{EOD}) and has no distinct relationship with initial pile resistance (R_{EOD}) as illustrated in Figure 5 (i.e., a poor R^2 of 0.11 for WEAP-SA and a moderate R^2 of 0.67 for CAPWAP), it is reasonable to discount their relationship. Additionally, Eq. (1) indicates that the amount of pile resistance gain ($\Delta R_t = R_t - R_{EOD}$) at a given t and R_{EOD} is related to the pile setup factor (C) or

$$C \propto \Delta R_t \quad (2)$$

Assuming the dissipation of excess pore water pressure mainly occurs horizontally along the embedded pile length, Soderberg (1962) suggested that the increase in pile resistance (ΔR_t) could be related to a non-dimensional time factor T_h given by

$$\Delta R_t \propto T_h = \frac{C_h t}{r_p^2} \quad (3)$$

where r_p is the pile radius or equivalent pile radius based on cross sectional area; and C_h is the horizontal coefficient of consolidation. This relationship is consistent with the observation made in the companion paper where increase in pile resistance (ΔR) is proportional to C_h . Additionally, the field test results indicated an inverse relationship between the increase in pile resistance (ΔR) and the undrained shear strength and SPT N -value. Results presented in the companion paper also showed that pile setup mostly occurs along the pile shaft and its effect on the end bearing is insignificant. Therefore, to account for the variation in soil property and its respective thickness, only cohesive soil layers along the pile shaft were considered in the calculation of weighted average soil property. For instance, the weighted average SPT N -value (N_a) is calculated by weighing the measured uncorrected N -value (N_i) at each cohesive soil layer i along the pile shaft by its thickness (l_i) for a total of n cohesive layers situated along the embedded pile length. This is expressed as

$$N_a = \frac{\sum_{i=1}^n N_i l_i}{\sum_{i=1}^n l_i} \quad (4)$$

It has been previously established that the pile setup factor (C) for a specific site can be assumed to be independent of time (t) and R_{EOD} . Therefore, Eq. (2) can be presented by replacing (ΔR_t) with the weighted average horizontal coefficient of consolidation (C_{ha}) and the weighted average SPT N -value as shown in Eq. (5).

$$C \propto \frac{C_{ha}}{N_a r_p^2} \quad (5)$$

The C_{ha} value in Eq. (5) is a weighted average value calculated using an equation similar to Eq. (4), in which the C_h value at each cohesive soil layer was estimated from pore water pressure

dissipation tests during Piezocone Penetration Test (CPT) and calculated using the strain path method reported by Houlsby and Teh (1988). When pore water pressure dissipation tests are not performed, C_h can be estimated from the respective undrained shear strength (S_u) in kPa or the uncorrected SPT N -value based on the correlation study discussed in the companion paper using Eq. 6 or 7, respectively.

$$C_h(\text{cm}^2/\text{min}) = \frac{264.76}{(S_u)^{1.928}} \quad (6)$$

$$C_h(\text{cm}^2/\text{min}) = \frac{3.18}{N^{2.08}} \quad (7)$$

It is important to note that Eq. (6) and Eq. (7) are not applicable for cohesive soils with S_u value smaller than 50 kPa and SPT N -value smaller than 5, respectively, which could yield a difference of at least 10% in the pile setup resistance estimation proposed in the later section. The weighted average soil parameters (C_{ha} and N_a) are listed in Figure 6. An equivalent pile radius (r_p) of 5.05 cm was calculated from the 80-cm² cross-sectional area of HP 250 × 62. Plotting the C values determined from Figure 3 for CAPWAP and from Figure 4 for WEAP-SA with the $\frac{C_{ha}}{N_a r_p^2}$ values in Figure 6, the relationship for Eq. (5) can be expressed as follows:

$$C = f_c \left(\frac{C_{ha}}{N_a r_p^2} \right) + f_r \quad (8)$$

where f_c is the consolidation factor, and f_r is the remolding recovery factor. These two values are included in Figure 6 for both the CAPWAP and WEAP-SA results for the five test piles. Since the pile setup is influenced by the superposition of soil consolidation and recovery of the surrounding remolded soils, the effect of soil consolidation is best described by the first term (i.e., $\frac{f_c C_{ha}}{N_a r_p^2}$) and the effect of recovery of the remolded soils is best accounted for by the remolding recovery factor, f_r .

Proposed Method

Substituting the rate of pile setup (C) expressed in Eq. (8) into pile setup Eq. (1), the following pile setup equation can be established:

$$\frac{R_t}{R_{EOD}} = \left[\left(\frac{f_c C_{ha}}{N_a r_p^2} + f_r \right) \log_{10} \left(\frac{t}{t_{EOD}} \right) + 1 \right] \left(\frac{L_t}{L_{EOD}} \right) \quad (9)$$

In comparison to the existing pile setup methods that were previously summarized, the proposed

method in Eq. (9) has the following advantages:

1. It uses a reference pile resistance at EOD that is estimated using either WEAP-SA or CAPWAP, thus eliminating any restrrike requirements;
2. It defines variable t as the actual lapsed time following the completion of the pile installation and uses a well-defined t_{EOD} of 1 minute;
3. It incorporates measureable soil parameters that can be obtained from SPTs and CPTs to estimate rate of pile setup;
4. It does not require any field testing following pile installation;
5. It accounts for variation in soil parameters between different layers of soils along the pile shaft; and
6. Although the equation was established primarily using the recent ISU field tests conducted on one type of steel H-pile (i.e., HP 250 \times 62) embedded in cohesive soils, it is subsequently shown that it can be used for other pile sizes and types.

As with any setup formula based on soil properties, it is noted that the proposed method is only applicable for cohesive soils in which soil setup has been verified to occur by either restrikes or static testing.

VALIDATION

This section examines the validity of the proposed setup equation using data available from PILOT as well as in literature. Different sizes of steel H-piles and other pile types are given consideration in this investigation.

Steel H-Piles

The steel H-pile data available from Iowa via PILOT (Roling et al., 2010) and literature is examined in this subsection. The PILOT database contains twelve pile data sets in cohesive soils having sufficient pile, soil, and hammer information for pile setup evaluations using WEAP-SA. However, the database does not contain any Pile Driving Analyzer (PDA) records required for CAPWAP analysis. Table 2 summarizes the essential information for the twelve steel H-piles. These piles are the most frequently used pile type in Iowa (i.e., HP 250 \times 62) with the exception of one, which was HP 310 \times 79. The piles were embedded primarily in cohesive soils. Since CPTs with dissipation tests were not performed at each site, the SPT N -values obtained along the

pile length were used to estimate the corresponding C_h values from Eq. (7), while the C_{ha} value was similarly calculated for N_a using Eq. (4). SLTs on these piles were performed between 1 and 8 days after EOD, and the measured pile resistances were determined based on Davisson's criterion (Davisson, 1972). The pile resistance corresponding to the time of SLT (R_t) was estimated using Eq. (9). The pile resistances at EOD condition (R_{EOD}) were estimated using the WEAP-SA method.

In addition, five well-documented steel H-piles tested by other researchers were selected for use in examining the validity of Eq. (9), as summarized in Table 3. This set includes three different pile sizes: HP 250, HP 310 and HP 360. Again, the C_{ha} values were estimated from SPT N -values using Eqs. (4) and (7), except the C_{ha} value of $0.025 \text{ cm}^2/\text{min}$ for Lukas and Bushell (1989), which was estimated using a combination of Eqs. (4), (6) and (7). The measured pile resistances determined either from SLTs or restrikes were reported by the different authors and are included in Table 3 with the time of test or restrike. Corresponding to each time of restrike or SLT, the pile resistance (R_t) was estimated using Eq. (9). The estimated pile resistances at the EOD condition (R_{EOD}), using both CAPWAP and/or WEAP-SA methods provided in literature, are also listed in this table. In three cases marked with a superscript "a", the R_{EOD} values were estimated using WEAP-SA as part of this study using the provided information.

Using the information provided in Table 2 and Table 3, as well as the results of the five field tests conducted by the research team, Figure 7 and Figure 8 compare the measured pile resistances (R_m) with estimated pile resistances at time t (R_t). The R_t values were determined by adding the pile resistance estimated at EOD condition (R_{EOD}) with the pile setup resistance (R_{setup}) estimated using the proposed pile setup Eq. (9) at time t of the SLTs or restrikes based on the CAPWAP and WEAP-SA methods, respectively. In each figure, a linear best-fit line, calculated using a regression analysis, is represented by a dashed line and is compared with a solid line, thus indicating the line of equality. Both figures show that the proposed pile setup method significantly improved the pile resistances by having the best-fit lines closer to the lines of equality, and by having the mean of a resistance ratio (i.e., a ratio of measured to estimated pile resistance) closer to unity and a smaller coefficient of variation (COV). Furthermore, it should be emphasized that even though the proposed pile setup method was developed for one steel H-pile size (HP 250 \times 62), the results presented in Figure 7 and Figure 8 yield good

predictions for other H-pile sizes. Comparing with the beginning of restrike (BOR) approach in terms of the statistical characteristics (i.e., mean and *COV*) of the pile resistance ratio given in Figure 7, the proposed setup method, which resulted in a mean value of 1.024 closer to unity and a smaller *COV* of 0.149, is comparable or even superior to the BOR approach.

To avoid the bias created with local conditions, a comparison was conducted between the measured pile resistances (R_m) and estimated pile resistances, including pile setup as per Eq. (9) (R_t) in terms of pile resistance ratios (R_m/R_t), based on the external data alone. This is summarized in Table 3. Normal distribution curves of the resistance ratio (R_m/R_t) are presented in Figure 9 for both CAPWAP and WEAP-SA. A similar statistical evaluation was performed based on pile resistance ratios for the EOD condition (R_m/R_{EOD}). Comparing the normal distribution curves for the EOD condition (R_m/R_{EOD}) and accounting for pile setup (R_m/R_t), Figure 9 shows the shifting of the mean values (μ) towards unity (from 1.53 to 1.04 for CAPWAP and 1.78 to 1.06 for WEAP-SA) and the reduction in *COV* (from 0.21 to 0.17 for CAPWAP and from 0.22 to 0.19 for WEAP-SA). These statistical assessments and corresponding observations provide further evidence that the proposed pile setup Eq. (9) has reasonably and consistently predicted the increase in pile resistances in different cohesive soil conditions for steel H-piles of differing sizes.

Other Pile Types

An assessment was also performed to evaluate the application of the proposed method on other pile types installed in cohesive soils. Six well-documented cases were used for this purpose, as summarized in Table 4. Other pile types comprised of closed-end pipe piles (CEP), open-end pipe piles (OEP), square precast prestressed concrete piles (PCP), and steel monotube piles (SMP). The maximum dimension (i.e., width or diameter) of these piles was generally quite large and ranged from 244 mm to 750 mm. To differentiate between the small and large displacement piles, a pile area ratio (*AR*) (i.e., a ratio between pile embedded surface area and pile tip area) was calculated for each pile type and compared with a quantitative boundary of 350, as suggested by Paikowsky et al. (1994). Since the largest estimated *AR* of 278 for the 273-mm OEP was smaller than 350, all of the piles were classified as large displacement piles, whereas the corresponding values for the steel H-piles in Table 2 and Table 3 were between 908 (for HP 250 × 62) and 4754 (for HP 360 × 174), assuming no soil plugging near the pile toe

which was confirmed by our observation of the retrieved test pile ISU3.

The comparison between pile resistances obtained during restrikes and SLTs (R_m) are plotted in Figure 10 as a function of pile resistance reported at EOD (R_{EOD}). The R_{EOD} values were estimated using CAPWAP, with the exception of those reported by Thompson et al. (2009), which were estimated using PDA based on an assumed Case damping factor of 0.85. It is evident that the R_m values are larger than R_{EOD} values (most data points above the solid line of equality), confirming the occurrence of pile setup and its increasing trend with time. Using the reported R_{EOD} value, the estimated average SPT N -value (N_a) calculated using Eq. (4), the average horizontal coefficient of consolidation (C_{ha}) obtained from Eqs. (4) and (7), and the pile radius (r_p), a pile resistance was estimated using the proposed pile setup Eq. (9) at the time of restrike or SLT. When incorporating estimated pile setup in addition to the R_{EOD} value, Figure 11 reveals the data points represented with a linear best-fit dashed line shifted closer to the solid line of equality, indicating the close match between the measured and estimated pile resistances. The numerical values of the data points plotted in Figure 11 are summarized in Table 5.

For comparative purposes, the means (μ) and COV of pile resistance ratios for both the EOD condition (R_m/R_{EOD}) and the proposed setup method (R_m/R_t) were calculated for the entire data set, as well as for the following two pile categories: (1) pile sizes equal to and greater than 600-mm (i.e., large diameter piles); and (2) pile sizes smaller than 600-mm (i.e., small diameter piles). This grouping was established purely based on the observed distribution of data. Based on the μ and COV values summarized in Figure 10, the large diameter piles appear to exhibit greater pile setup, as their μ value was about 0.21 units greater than that of smaller diameter piles. The consideration of pile setup using the proposed method not only reduces the μ values from 1.663 to 1.184 and from 1.454 to 1.063 for large and small diameter piles, respectively, but their COV values were also reduced by more than 6%. When comparing the μ and COV values corresponding to the CAPWAP approach for the steel H-piles in Figure 7 with the two groups of displacement piles in Figure 11, the smallest μ and COV values ($\mu = 1.024$ and $COV = 0.149$) are obtained for steel H-piles, followed by slightly higher values ($\mu = 1.063$ and $COV = 0.258$) for small diameter displacement piles, with the highest values ($\mu = 1.184$ and $COV = 0.334$) for large diameter displacement piles. This comparison suggests the proposed setup method provides a better pile setup prediction for steel H-piles and smaller diameter displacement piles than for

larger diameter displacement piles. However, it is noted that the significant scatter obtained for large diameter displacement piles is from the dataset of Thompson et al. (2009), in which R_{EOD} values were estimated using the PDA. When this data set was excluded, $\mu = 1.02$ and $COV = 0.248$ were obtained from the remaining data on small and large diameter displacement piles. However, in comparison to the BOR approach, the statistical parameters given in Figure 11 indicate that the restrike approach yields a better pile setup estimation, substantiating with a mean of 1.013 closer to unity and a smaller COV of 0.194.

CONFIDENCE LEVEL

To help implement the proposed pile setup method in practice, the reliability of the method was examined in order for the designers to recognize that the difference between the actual and estimated pile setup values fall within an acceptable tolerance. The confidence of the method in terms of pile resistance ratio (R_m/R_t) can be expressed for different confidence levels as:

$$\left(\frac{R_m}{R_t}\right)_{\text{upper bound}} = \mu + z \times \frac{\sigma}{\sqrt{n}}; \left(\frac{R_m}{R_t}\right)_{\text{lower bound}} = \mu - z \times \frac{\sigma}{\sqrt{n}} \quad (10)$$

where μ is the mean value of the pile resistance ratio; z is the standard normal parameter based on a chosen percent of confidence interval (CI); σ is the standard deviation of the pile resistance ratio; and n is the sample size. Using the statistical parameters (μ and σ) reported in Figure 7 and Figure 8 for steel H-piles, the upper and lower limits of the population mean values of pile resistance ratios for 80%, 85%, 90%, 95%, and 98% CI s were calculated using Eq. (10) and plotted in Figure 12. This shows that the upper limits increase while the lower limits decrease as the value of CI increases from 80% to 98%. In an attempt to determine the amount of pile setup that can be confidently applied directly to production piles in the State of North Carolina, Kim and Kreider (2007) suggested the use of 98% and 90% CI s for individual steel H-piles and pile groups with redundancy, respectively, based on their field observations. Applying this recommendation, the pile resistance ratio (R_m/R_t) for CAPWAP was found to vary between 0.94 and 1.11 for individual piles at 98% CI . Hence, there is 98% confidence that the proposed pile setup Eq. (9) will predict the R_t with an error falling between -6% and 10% of the R_m when used in conjunction with CAPWAP. A similar explanation applies to WEAP-SA at a 98% CI , in which the error falls between -7% and 8% of R_m . Similarly, in the case of a redundant pile group based on 90% confidence, the errors fall between -5% and 6% of R_m for the WEAP-SA method

and between -8% and 4% of R_m for the CAPWAP method.

For individual displacement piles at a 98% CI based on the proposed pile setup Eq. (9) when used in conjunction with CAPWAP, Figure 13 shows that R_m/R_t for small diameter piles ranges between 0.97 and 1.16, while R_m/R_t for large diameter piles ranges between 1.03 and 1.34. Hence, there is 98% confidence that R_t will be estimated with errors between -14% and 3% of R_m for small diameter piles and between -25% and -3% of R_m for large diameter piles. For a redundant pile group at 90% CI , the errors fall between -11% and 0% of R_m for small diameter piles and between -23% and -7% of R_m for large diameter piles. These evaluations also indicate that the pile setup estimation for displacement piles yields relatively higher percentages of error.

INTEGRATION OF PILE SETUP INTO LRFD

The AASHTO LRFD Bridge Design Specifications (2010) recommended a single resistance factor (ϕ) for each dynamic analysis method, because the measured nominal pile resistance obtained from the dynamic pile restrike test is assumed to be a single random variable. Alternatively, the proposed method (Eq. (9)) consists of two resistance components (i.e., R_{EOD} and R_{setup}). Since each resistance component has its own individual uncertainties, such as those resulting from the in-situ measurement of soil properties, the components should be adequately reflected in the resistance factors in order to remain consistent with the LRFD philosophy. Therefore, it is conceptually inappropriate to establish a single resistance factor for both resistance components. Yang and Liang (2006) used the First Order Reliability Method (FORM) to determine separate resistance factors, specifically for Skov and Denver's (1988) setup equation. Yang and Liang (2006) recommended a resistance factor of 0.30 for pile setup resistance for redundant pile groups. This issue will be further investigated and an appropriate resistance factor will be established for use with Eq. (9) in a future publication.

CONCLUSIONS

Although pile setup depends on the properties of the surrounding soil, the existing pile setup estimation methods available in literature rarely consider soil properties and usually require inconvenient restrikes to accurately estimate the pile setup. These limitations and the successful correlation between pile setup and soil parameters described in the companion paper (Ng et al.,

2011) led to development of a new pile setup method. From the analyses of the pile and soil test data and through examining the validation of the proposed setup equation, the following conclusions resulted:

1. Although the pile setup estimation methods proposed by Skov and Denver (1988) and Karlsrud et al. (2005) were shown to be satisfactory for specific soil types, they failed to provide good estimates of the setup for recently collected data on steel H-piles embedded in cohesive soils.
2. In the absence of a reliable and cost-effective method to estimate pile setup, a new method has been proposed using pile geometry and soil properties along a pile shaft that can be obtained from typical SPTs and/or CPTs as the main variables. The main economic benefit of the proposed method is the fact that the setup estimation uses a reference pile resistance at EOD, which was obtained, based on either WEAP-SA or CAPWAP and does not require any restrrike.
3. Using field records for steel H-piles of different sizes available in the PILOT database and literature, the proposed method has been found to accurately estimate the effects of the pile setup even though the proposed pile setup method was developed primarily based on one type of steel H-pile (HP 250 \times 62). For a non-redundant pile group, the proposed method is expected to produce pile setup estimations accurately with an expected error of only $\pm 8\%$, on average, when used in conjunction with WEAP-SA and CAPWAP.
4. The analysis based on six cases of displacement piles found in literature shows that the proposed pile setup method produced satisfactory pile setup estimations when used in conjunction with CAPWAP. For non-redundant pile groups, the errors of pile resistance estimations for small and larger diameter displacement piles were somewhat higher, ranging between -14% and 3%, and -25% and -3% of the measured resistances, respectively.
5. The results of the statistical analyses concluded that the proposed setup method provides a better pile setup prediction for steel H-piles and smaller diameter displacement piles than for larger diameter displacement piles. This was demonstrated by the smaller errors of 8% for steel H-piles and 14% for small diameter displacement piles than 25% for large diameter displacement piles.

Despite the successful demonstration, the proposed setup method should be used for piles in cohesive soils, for which the setup has been verified to occur by either restrikes or static load testing. When C_{ha} is based on SPT- N values, the accuracy of the proposed method will be dictated by the reliability of the SPT- N values. Furthermore, it should be noted that the method will yield non-conservative results for pile resistance in soils, which either do not gain setup resistance or do experience soil relaxation.

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Table 1. Summary of existing methods of estimating pile setup

Reference	Setup Equation	Limitations
Pei and Wang (1986)	$\frac{R_t}{R_{EOD}} = 0.236[\log(t) + 1] \left(\frac{R_{max}}{R_{EOD}} - 1 \right) + 1$	<ul style="list-style-type: none"> – Purely empirical – Site specific – No soil property – Unknown or difficult to determine R_{max}
Zhu (1988)	$\frac{R_{14}}{R_{EOD}} = 0.375S_t + 1$	<ul style="list-style-type: none"> – Only predicts pile resistance at 14th day – No consolidation effect is considered
Skov and Denver (1988)	$\frac{R_t}{R_o} = A \log \left(\frac{t}{t_o} \right) + 1$	<ul style="list-style-type: none"> – Requires restrikes – Wide range and generic A value
Svinkin and Skov (2000)	$\frac{R_t}{R_{EOD}} = B[\log(t) + 1] + 1$	<ul style="list-style-type: none"> – Requires restrikes – B value has not been extensively quantified – No clear relationship between B value and soil properties
Karlsrud et al. (2005)	$\frac{R_t}{R_{100}} = A \log \left(\frac{t}{t_{100}} \right) + 1 ;$ $A = 0.1 + 0.4 \left(1 - \frac{PI}{50} \right) OCR^{-0.8}$	<ul style="list-style-type: none"> – Assumed complete dissipation after 100 days is not accurate – Not practical to use R_{100}

Note: R_t = pile resistance at any time t considered after EOD; R_{EOD} = pile resistance at EOD; R_{max} = maximum pile resistance assumed after complete soil consolidation; R_o = reference pile resistance; R_{14} = pile resistance at 14 days after EOD; R_{100} = pile resistance at 100 days after EOD; S_t = soil sensitivity; A = pile setup factor defined by Skov and Denver (1988); B = pile setup factor defined by Svinkin and Skov (2000); PI = plasticity index; and OCR = overconsolidation ratio.

Table 2. Summary of the twelve data records from PILOT

Project ID	County in Iowa	Pile type	Emb. pile length (m)	Hammer type	Soil profile description	Ave. SPT N -value, N_a	Est.ave. C_{ha} using Eqs. (4) and (7) (cm^2/min)	Time after EOD, t (day)	WEAP-SA est. pile resis. at EOD (kN)	SLT pile resis. at t (kN)	Est. pile resis. at t (kN)	Ave. AR
6	Decatur	HP250×62	16.16	Gravity #732	Glacial clay	14.47	0.0407	3	323	525	500	2050
12	Linn	HP250×62	7.25	Kobe K-13	Glacial clay	29.90	0.0029	5	679	907	1070	920
42	Linn	HP250×62	7.16	Kobe K-13	Glacial clay	22.20	0.0095	5	375	365	592	908
44	Linn	HP250×62	11.13	Delmag D-22	Sandy silty clay	22.34	0.0053	5	410	605	647	1412
51	Johnson	HP250×62	8.99	Kobe K-13	Silt/glacial clay	40.00	0.0014	3	562	845	867	1140
57	Hamilton	HP250×62	17.38	Gravity #2107	Glacial clay	9.77	0.0302	4	405	747	636	2204
62	Kossuth	HP250×62	13.72	MKT DE-30B	Glacial clay	36.05	0.0180	5	335	445	529	1740
63	Jasper	HP250×62	19.21	Gravity	Silt/glacial clay	8.32	0.0429	2	265	294	404	2437
64	Jasper	HP250×62	21.65	Gravity	Silt/glacial clay	10.52	0.0309	1	320	543	473	2746
67	Audubon	HP250×62	9.76	Delmag D-12	Glacial clay	20.00	0.0060	4	542	623	846	1238
102	Poweshiek	HP250×62	13.11	Gravity #203	Silt/glacial clay	16.45	0.0400	8	372	578	600	1663
109	Poweshiek	HP310×79	15.55	Delmag D-12	Glacial clay	17.36	0.0132	3	673	783	1041	1895

Table 3. Summary of five external sources from literature on steel H-piles embedded in cohesive soils

Reference; Location	Pile type	Emb. pile length (m)	Hammer type	Soil profile description	Ave. SPT N_a value, N_a	Est. ave. C_{ha} using Eqs. (4) and (7) (cm ² /min)	Time after EOD , t (day)	Mea. pile resis. at t from SLT or restrikes (kN)	Est. pile resis. at t (kN)	CAPWAP est. pile resis. at EOD (kN)	WEAP- SA est. pile resis. at EOD (kN)	Ave. AR
Huang (1988); China	HP360×174	74.2	Kobe KB60	Silty clay to clay over silty sand	6.13	0.873	1.67 31	4485 ^e 7250 ^d	5150 5874	2983	3220 ^a	4754
Lukas & Bushell (1989); Illinois	HP250×62	25.6	Vulcan 80C	Fill overlaying soft to hard clay	$N=10$ $S_u=108$ to 1197 kPa ^b	0.025 ^b	10 26	1139 ^d 1308 ^d	1089 1131	-	671 ^a	3250
Long et al. (2002); Illinois	HP310×79	9.4 to 11.5	Delmag D19-32	Silty clay/loam overlaying sandy till	6.63	0.291	7 22	1202 ^d 2537 ^d	1966 2902	1068 1472 ^c	1174 1677 ^c	1143 to 1407
Fellenius (2002); Canada	HP310×110	70	Delmag D30-32	Mixture of sand, silt and clay overlaying glacial till	13.57	0.076	7 13 15 16 18 21 28 32 44	2300 ^e 2500 ^e 2570 ^e 2821 ^e 2714 ^e 2554 ^e 3000 ^e 3107 ^e 3071 ^e	2150 2204 2217 2222 2233 2246 2272 2283 2311	1917	1339 ^a	2660
Kim & Kreider (2007); North Carolina	Structures 3 & 4: HP310 ×79 & HP 360×108 Structure 5: HP310×79	24.4 to 30.2	Delmag D19-42	Sand overlaying silty clay and clayey silt	10.06	0.048	1 2 3 4 6 1	1380 ^f 1538 ^f 1607 ^f 1519 ^f 1471 ^f 1144 ^f	1454 1764 2339 1439 1548 1128	- - - - - 649	984 1157 1508 916 970 763	2974 to 4295

^aPile resistance estimated by research team based on reported hammer blow rate.^bEstimated using a combination of Eqs. (4), (6) and (7) based on $N=10$ for 13.4 m thick, $S_u=108$ kPa for 9.15 m thick and $S_u=1197$ kPa for 3.05 m thick.^cEstimated pile resistance at EOD condition taken 7 days after the pile installation.^dMeasured pile resistance using SLT based on Davisson's criteria.^ePile resistance estimated using CAPWAP during restrrike.^fAn average pile resistance estimated using WEAP during restrikes.

Table 4. Summary of six external sources from literature on other pile types embedded in cohesive soils

Reference; Location	Pile types	No. of piles	Average embedded pile length (m)	Hammer type	Soil profile description	Ave. SPT N_a - value, N_a	Ave. AR
Cheng and Ahmad (2002); Ontario-Canada	244-mm × 13.8-mm CEP	1	14.3	Berming B-400	Silt to clayey silt and sandy silt	34 (Site 3)	115
Karna (2001); Newark-New Jersey	600-mm × 12.5-mm CEP	12	36.9 to 48.9	ICE 206S	Glacial deposit with clayey silt and clay	23 (South) and 36 (North)	136
Fellenius (2002); Alberta- Canada	273-mm OEP	1	24.0	-	Silt and clay overlying clay till	30	278
	273-mm CEP	1	24.0				176
	324-mm CEP	1	36.7				227
	356-mm square PCP	1	30.0				169
Thibodeau and Paikowsky (2005); Connecticut	406-mm square PCP	3	30.6, 34.9 and 35.2	HMC 86 and HPSI 2000	Organic silt overlying glacio-deltaic deposit	15 (Area A) and 20 (Area B)	165
	457-mm SMP	2	28.9 and 36.7				124
	457-mm CEP	3	36.3, 37.0 and 43.1				170
	610-mm CEP	1	47.9				157
Kim et al. (2009); Indiana	356-mm × 12.7-mm CEP	3	17.4 to 18.1	ICE 42S	Silty sand, silty clay overlying clayey silt	22 (S1) and 35 (S2)	100
Thompson et al. (2009); Mississippi	600-mm square PCP	7	25.9 to 32.0	Delmag 30-32, DKH-10U, Conmaco 5200, and Conmaco 300E	Low and high plasticity clay with some layers of clayey sand	6	190
	750-mm square PCP	3	27.7, 29.3 and 29.3				151

Note: CEP—Closed end steel pipe pile; OEP—Opened end steel pipe pile;
PCP—Precast prestressed concrete pile; SMP—Steel monotube pile.

Table 5. Summary of measured and estimated pile resistances for other pile types listed in Table 4

Reference; Location	Pile types	BOR/ SLT	Measured Pile Resistance in kN (Time after EOD)	Estimated pile resistance R_t in kN (Time after EOD)
Cheng and Ahmad (2002); Ontario-Canada	244-mm \times 13.8-mm CEP	BOR	2230(1)	2325(1)
		SLT	2400(1)	2325(1)
Karna (2001); Newark-New Jersey	600-mm \times 12.5-mm CEP	BOR	4715(5); 4995(5); 5160(5); 4724(10); 4938(11); 3648(13); 3665(14); 3914(14); 3981(14); 4226(14); 5293(14); 4244(26); 4399(27); 4537(27); 4226(29); 4381(29)	5154(5); 5184(5); 5660(5); 5468(10); 4600(11); 4327(13); 4422(14); 5201(14); 5262(14); 4978(14); 3582(14); 4978(26); 4415(27); 5739(27); 4511(29); 5306(29)
		SLT	5783(6); 5338(28)	5690(6); 4420(28)
Fellenius (2002); Alberta- Canada	273-mm OEP	BOR	1500(0.63)	1071(0.63)
	273-mm CEP	BOR	1550(0.63)	1197(0.63)
Thibodeau and Paikowsky (2005); Connecticut	324-mm CEP	BOR	1320(1); 1437(10)	1706(1); 1823(10)
		SLT	1592(56)	1911(56)
	356-mm square PCP	BOR	2691(1)	2725(1)
		SLT	2180(42)	3030(42)
	406-mm square PCP	BOR	2856(1); 3461(1); 3581(1); 3554(8); 3132(11); 3670(23)	2701(1); 3953(1); 2308(1); 2871(8); 2475(11); 4342(23)
		SLT	2816(41); 2669(44); 2847(45)	2567(41); 4401(44); 3012(45)
Thompson et al. (2009); Mississippi	457-mm SMP	BOR	1423(1); 1632(1); 1797(9); 1935(12)	1575(1); 1482(1); 1679(9); 1593(12)
		SLT	2002(54); 2771(55)	1661(54); 1764(55)
	457-mm CEP	BOR	1615(1); 1953(1); 2197(1); 2807(7); 2335(14); 2660(15)	2045(1); 2482(1); 2929(1); 3099(7); 2207(14); 2684(15)
		SLT	2269(45); 1957(50); 3025(50)	2766(45); 2285(50); 3272(50)
	610-mm CEP	BOR	2891(1); 3212(12)	3617(1); 3887(12)
		SLT	3683(54)	4051(54)
Kim et al. (2009); Indiana	356-mm \times 12.7-mm CEP	BOR	1053(1); 1081(1); 1220(2); 1202(7); 1102(8); 1242(10); 1486(35); 1840(104); 2104(107); 2254(127); 2082(134); 2283(154);	1123(1); 122891); 1147(2); 1189(7); 1305(8); 1201(10); 1243(35); 1280(104); 1400(107); 1406(127); 1288(134); 1293(154);
		SLT	1094(50); 1313(90)	1291(50); 1311(90)
Thompson et al. (2009); Mississippi	600-mm square PCP	BOR	5583(10); 6263(17); 4026(21); 6152(22); 5583(25); 6450(27); 6210(29); 5774(33); 6966(46);	3708(10); 5030(17); 2723(21); 3184(22); 3346(25); 3819(27); 3647(29); 2941(33); 5168(46)
		SLT	6183(19); 6219(22)	3602(19); 2906(22)
	750-mm square PCP	BOR	6744(6); 6414(9); 7113(23)	5050(6); 4426(9); 6639(23)
		SLT	6428(24)	6647(24)

Note: CEP—Closed end steel pipe pile; OEP—Opened end steel pipe pile; PCP—Precast prestressed concrete pile; SMP—Steel monotube pile

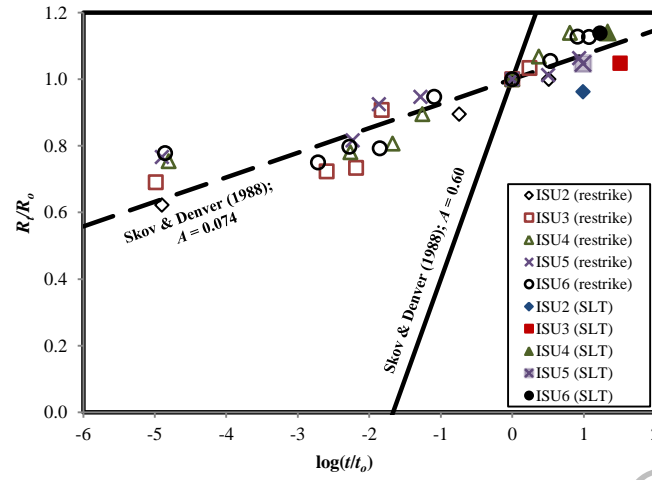


Figure 1. Comparison between ISU field test results and the Skov and Denver (1988) pile setup method

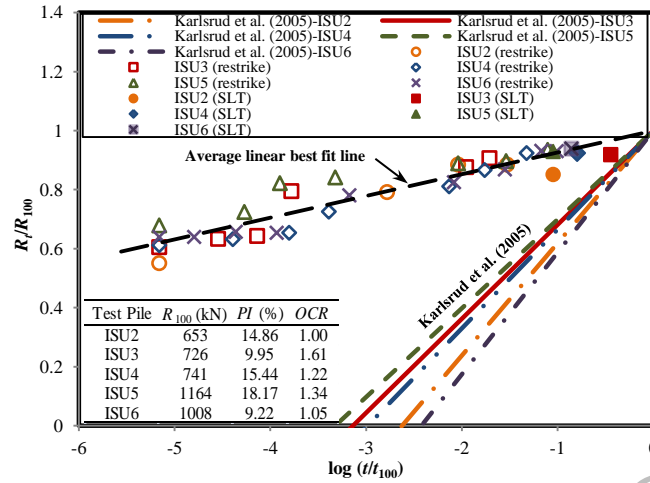


Figure 2. Comparison between ISU field test results and the Karlsrud et al. (2005) pile setup method

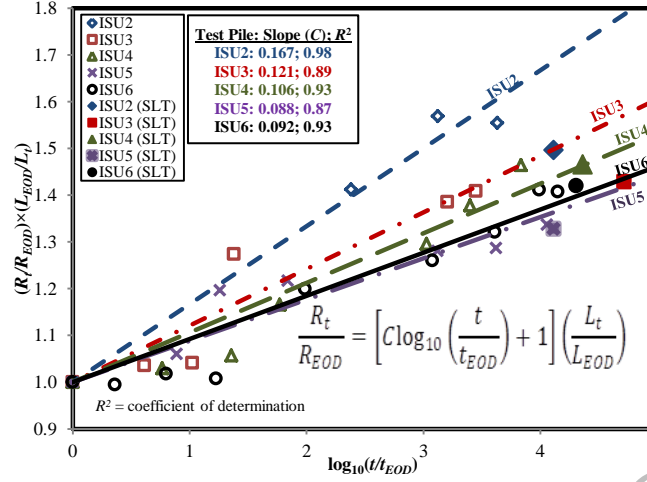


Figure 3. Linear best fits of normalized pile resistances as a function of logarithmic normalized time based on CAPWAP analysis

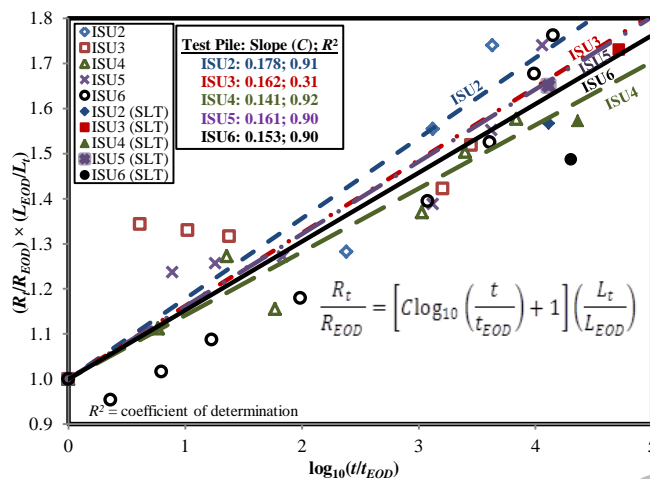


Figure 4. Linear best fits of normalized pile resistances as a function of logarithmic normalized time based on WEAP-SA analysis

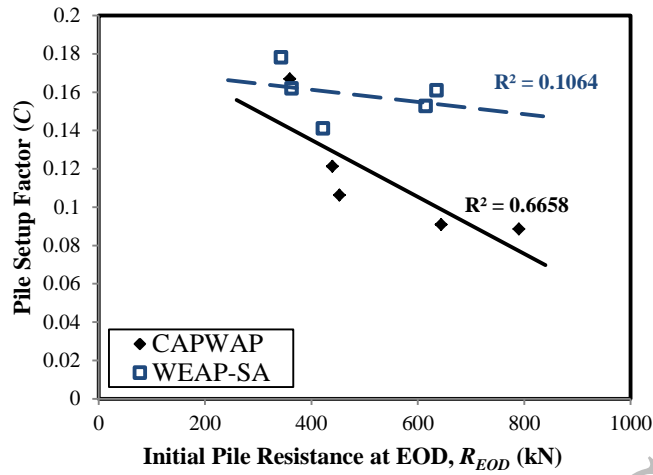


Figure 5. Comparison of pile setup factor (C) to initial pile resistance

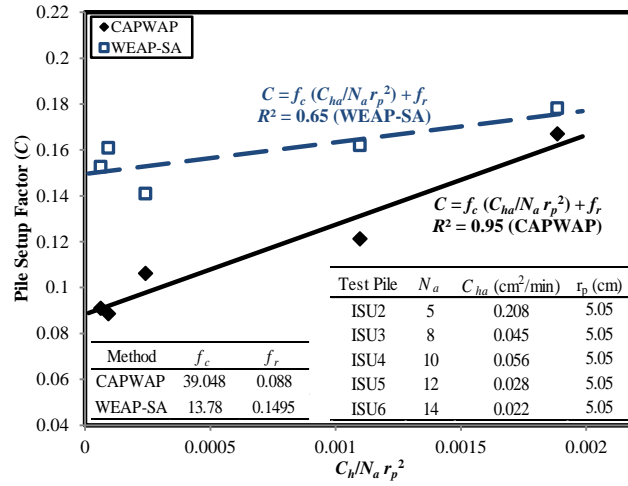


Figure 6. Correlations between pile setup factor (C) for different ISU field tests and soil parameters, as well as equivalent pile radius

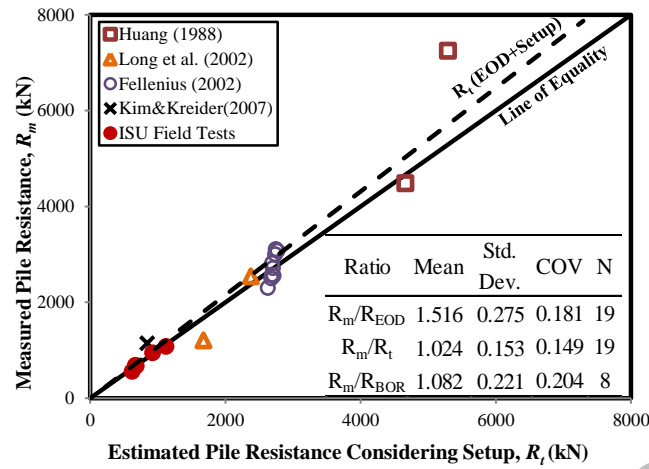


Figure 7. Comparison between measured pile resistances and estimated pile resistances for CAPWAP method

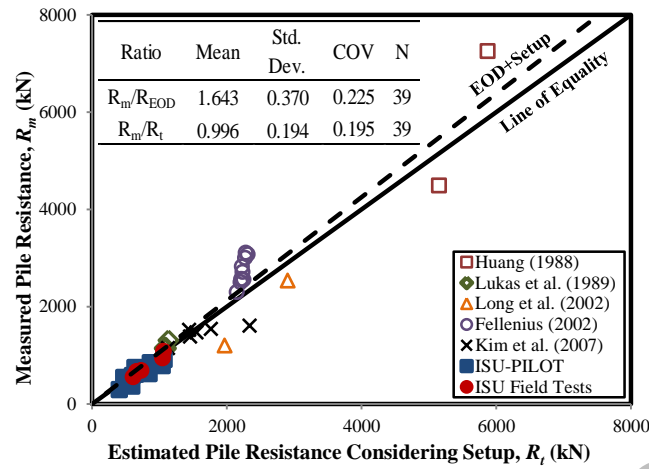


Figure 8. Comparison between measured pile resistances and estimated pile resistances for WEAP-SA

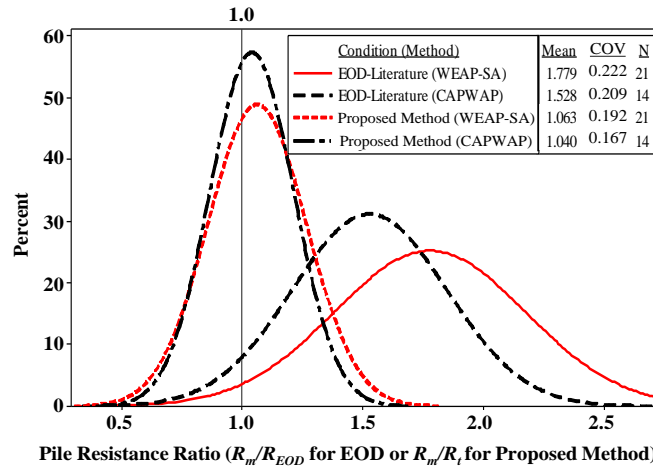


Figure 9. Statistical assessment of the proposed pile setup method based only on data reported in the literature as summarized in Table 3

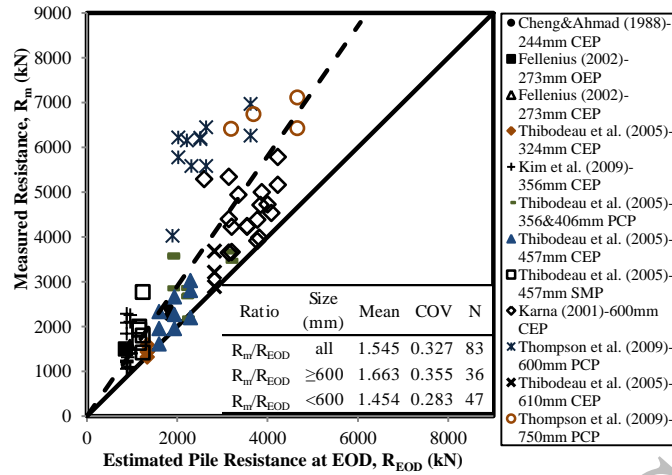


Figure 10. Comparison between measured pile resistances at any time (t) and reported pile resistances at EOD estimated using CAPWAP

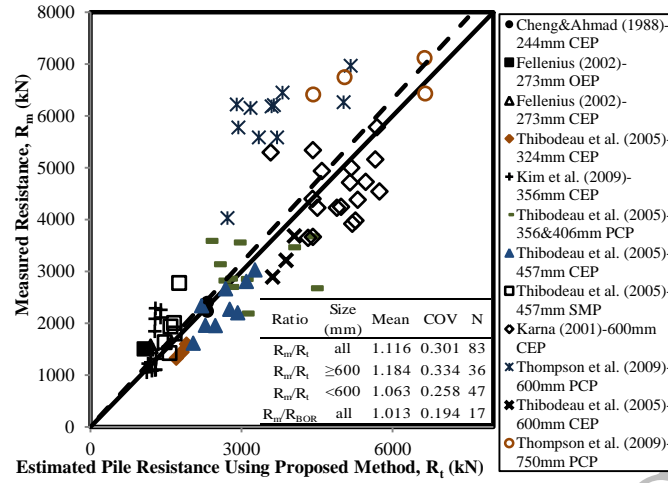


Figure 11. Comparison between measured pile resistances at any time (t), estimated pile resistances using CAPWAP for EOD plus the proposed pile setup method

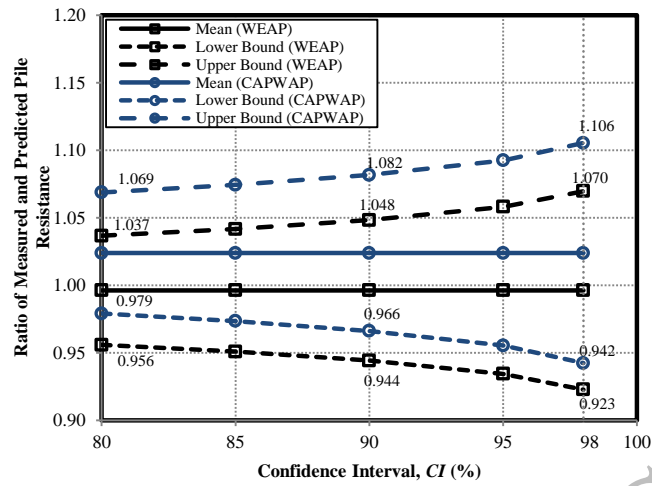


Figure 12. The confidence intervals of the proposed pile setup method for steel H-piles

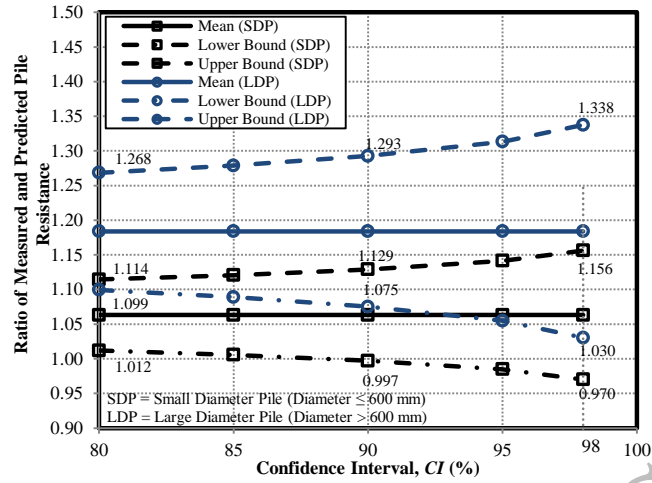


Figure 13. The confidence intervals of the proposed pile setup method for other small and large diameter displacement piles for CAPWAP